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Preface

The Space Programs Summary is a bimonthly publication that presents a review of engineering and scientific work performed, or managed, by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration during a two-month period. Beginning with the 37-47 series, the Space Programs Summary is composed of four volumes:

Vol. I. *Flight Projects* (Unclassified)

Vol. II. *The Deep Space Network* (Unclassified)

Vol. III. *Supporting Research and Advanced Development* (Unclassified)

Vol. IV. *Flight Projects and Supporting Research and Advanced Development* (Confidential)

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I. *Voyager* Project

PLANETARY–INTERPLANETARY PROGRAM

A. Evaluation of Maximum-Density Nitric Acid With an Impinging-Sheet Injector, *R. W. Riebling*

1. Introduction

Maximum-density fuming nitric acid (MDFA) is a mixture of 56% HNO_3 and 44% N_2O_4 by weight. Its physical properties are summarized in Ref. 1 and elsewhere. This oxidizer shows some promise as a sterilizable oxidizer for future spacecraft applications because, compared to other earth-storables (such as N_2O_4), it has a lower vapor pressure and a higher density at elevated temperatures.

As one part of a broader program to evaluate MDFA as a candidate oxidizer for the *Voyager* lander, a series of test-firings was conducted using two different candidate fuels: hydrazine (N_2H_4) and monomethylhydrazine (MMH). The injector chosen for performance evaluation was an existing 78-element, 2000-lbf thrust (at altitude) heavyweight impinging-sheet model. It had originally been designed for, and extensively fired with, N_2O_4/N_2H_4 propellants, so that a meaningful comparison of the combustion efficiencies attainable with the two oxidizers was possible. The earlier N_2O_4/N_2H_4 firings are described in SPS 37-41, Vol. V, pp. 7–19, and SPS 37-44, Vol. V, pp. 1–7.

Heretofore, the impinging-sheet injector had been fired at only a single nominal mixture ratio (1.2) and in an existing workhorse thrust chamber with a rather large characteristic length L^* of 39 in. In order to assess the effects of these two variables on the performance efficiency of the impinging-sheet injector as a combustion device, the propellant evaluation firings were conducted over a range of mixture ratios and characteristic chamber lengths.

2. Apparatus and Test Conditions

The impinging-sheet injector and uncooled 39-in.-L^* thrust chamber were described in SPS 37-41, Vol. V, pp. 7–19. A second chamber, having the same nozzle geometry as the first, but with built-in spool-like sections (so that its cylindrical length could be varied), was fabricated to determine the effect of characteristic length on combustion efficiency η_{c^*}. The additional characteristic lengths provided by this apparatus were 23.3 and 30.0 in. Unlike the 39-in.-L^* thrust chamber, however, the variable-L^* device was not instrumented with thermocouples for the measurement of nozzle and wall heat flux. The 39-in.-L^* chamber used with each of the two new propellant combinations was instrumented with flush-

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mounted, high-frequency response pressure transducers[1] to monitor combustion stability. However, as no spontaneous instabilities were noted, photocons were not used on the shorter chamber firings.

All firings were conducted at an ambient pressure of about 13.5 psia with an expansion area ratio of 2.43. Unlike previously reported firings, all 78 elements were used in the present series of tests. Chamber pressures ranged between about 75 and 150 psia, while mixture ratios varied from nominally 1.0 to about 1.8. All MDFA/N_2H_4 firings were made at a chamber L^* of 39 in.; the MDFA/MMH tests were conducted at 23.3, 30, and 39 in.

[1]Photocon Research Products, Model 307, Pasadena, California.

3. Experimental Results

The performance results are summarized in Tables 1 and 2. The durations reported are steady-state values. The use of the uncooled thrust chambers made short durations

Table 1. Results of firings with maximum-density fuming nitric acid and hydrazine (chamber characteristic length, $L^* = 39.1$ in.)

Test No.	Duration, s	Total flow rate $\dot{w}_t$, lbm/s	Mixture ratio, oxidizer/fuel	Chamber pressure P_c, psia	Thrust F, lbf	Pressure drops, psid		Fuel injection velocity, ft/s	R (Eq. 1)	Characteristic velocity c*, ft/s	Combustion efficiency η_{c^*}, %
						Oxidizer	Fuel				
1	1.5	6.90	1.20	156	1473	56	64	82.0	0.47	5570	96.1
2	1.6	6.59	1.27	159	1395	54	54	75.7	0.50	5570	96.4
3	2.0	6.64	0.96	150	1390	47	71	88.4	0.36	5550	95.8
4	1.9	6.97	1.72	151	1402	125	41	66.8	0.65	5320	95.7
5	2.1	4.56	1.23	102	856	28	26	53.2	0.49	5510	95.3
6	2.4	4.66	1.70	100	843	38	19	44.9	0.64	5285	95.1
7	2.4	4.45	0.98	101	570	22	32	58.7	0.37	5550	95.9
8	3.0	3.40	1.19	77	581	16	16	40.5	0.47	5530	95.6
9	3.0	3.53	1.72	76	566	24	12	33.9	0.65	5280	95.5
10	3.0	3.36	0.93	75	588	14	20	45.4	0.35	5780	95.4

Table 2. Results of firings with maximum-density fuming nitric acid and monomethylhydrazine

Test No.	Duration, s	Total flow rate $\dot{w}_t$, lbm/s	Mixture ratio, oxidizer/fuel	Chamber pressure P_c, psia	Thrust F, lbf	Chamber characteristic length L^*, in.	Pressure drops, psid		Fuel injection velocity, ft/s	R (Eq. 1)	Characteristic velocity c*, ft/s	Combustion efficiency η_{c^*}, %
							Oxidizer	Fuel				
1	3.0	6.68	1.19	143	1319	39.1	57	70	92.1	0.43	5250	96.0
2	3.1	7.03	1.39	154	1444	39.1	72	65	88.5	0.51	5370	96.1
3	3.5	4.62	1.22	98	834	39.1	31	32	62.6	0.45	5220	95.1
4	3.6	6.95	1.34	151	1420	30.0	63	69	89.4	0.49	5320	96.0
5	3.3	4.67	1.38	101	863	30.0	28	34	59.0	0.51	5315	95.6
6	3.2	3.61	1.42	78	605	30.0	17	22	44.7	0.52	5310	95.4
7	3.1	6.91	1.40	152	1420	23.3	70	61	86.5	0.51	5390	96.8
8	3.1	7.16	1.01	147	1362	23.3	58	91	107.0	0.36	5300	94.7
9	3.2	6.88	1.77	152	1428	23.3	84	44	74.8	0.63	5420	96.2
10	3.6	4.65	1.28	101	846	23.3	32	29	61.1	0.47	5300	96.2
11	4.1	4.98	0.98	102	863	23.3	30	43	75.5	0.34	5000	94.9
12	4.1	4.65	1.75	102	876	23.3	41	20	50.9	0.62	5390	96.2
13	4.6	3.50	1.30	75	573	23.3	20	17	45.8	0.48	5290	95.8
14	4.6	3.76	1.02	77	597	23.3	19	24	56.1	0.36	5040	94.9
15	4.6	3.43	1.72	75	570	23.3	24	12	37.8	0.62	5350	95.6

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mandatory. The chamber pressures reported are stagnation values, and were obtained from static measurements made near the entrance to the converging portion of the nozzle by applying the standard static-to-stagnation correction. The reported values of c^* are based on stagnation pressures, but no other corrections have been made to c^*. The tabulated values of η_{c^*} are included mainly for comparative purposes. They were calculated by comparing the uncorrected measured values to the theoretical full shifting equilibrium values at the experimental chamber pressures and mixture ratios.

4. Discussion

The experimental results are plotted in Fig. 1 against a normalizing parameter R

$$R = [1 + \phi]^{-1} \tag{1}$$

where

$$\phi = \left(\frac{1}{r}\right)^2 \left(\frac{\rho_o}{\rho_f}\right) \left(\frac{d_o}{d_f}\right)^3 = \frac{m_f/m_o}{d_f/d_o} \tag{2}$$

First introduced in Ref. 2, R has been found useful in correlating both cold-flow and hot-firing results for unlike-impinging doublet jet injectors. Over the range of R studied, which corresponds to mixture ratios from 1.0 to 1.8, η_{c^*} remained essentially constant and fairly high (95 to 96%) despite variations in injection velocities from 34 to 92 ft/s. Both propellant combinations gave essentially the same combustion efficiency, and characteristic length changes in the range $23 \leq L^* \leq 39$ in. did not appreciably influence performance. The high performance reported in the earlier SPS articles was therefore inherent in the basic injector design and did not result solely from the large values (39 in.) of characteristic chamber length originally used.

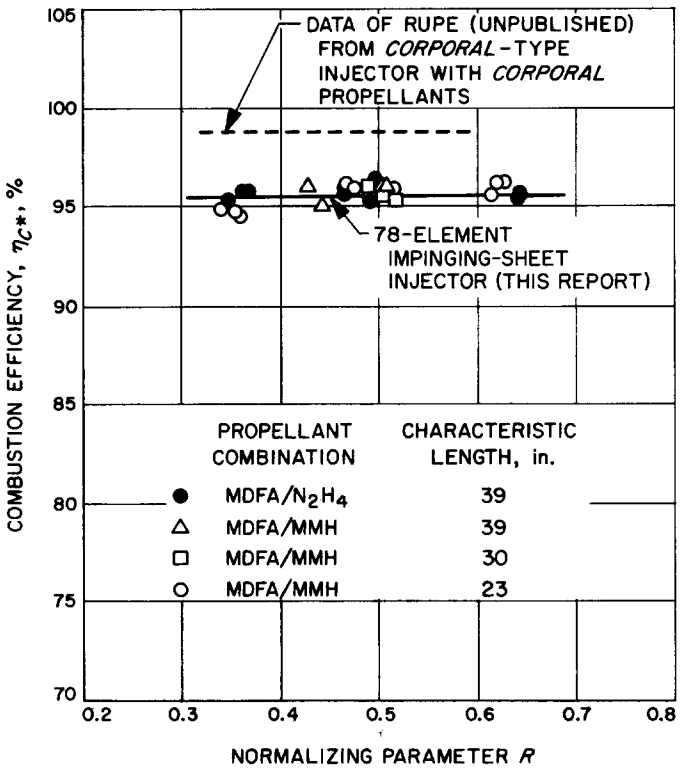

Fig. 1. Combustion efficiency versus normalizing parameter (Ref. 2) for multiple-element impinging-sheet and impinging-jet injectors

These results indicate that for the 78-element impinging-sheet injector, combustion efficiency is very insensitive to both injection velocity and R, for $0.35 \leq R \leq 0.65$. This behavior is not necessarily unique to multiple-element impinging-sheet injectors, however. For purposes of comparison, data from a 52-element *Corporal*-type unlike doublet impinging-*jet* injector[2] have also been plotted in Fig. 1. Over the same range of R the performance efficiency of the impinging-jet injector, which featured a degree of hydraulic control and reproducibility comparable to that of the sheet injector, also remained constant. (Absolute efficiency levels cannot be directly compared, of course, because of differences in propellants, chamber pressure, characteristic length, measurement techniques and data reduction.)

The results show comparable insensitivity of η_{c^*} to R for $0.35 \leq R \leq 0.65$ with both kinds of injector; in this range, impinging-sheets are therefore fully competitive with impinging jets. This insensitivity may be due in some measure to secondary mixing effects brought about in these multi-element injectors by interactions between adjacent spray fans. However, the behavior of single impinging-jet and impinging-sheet elements is quite different. The liquid-phase mixing of a pair of nonreactive unlike impinging sheets was reported in Ref. 3 to be manifestly insensitive to stream momentum ratio, while that of a pair of non-reactive unlike impinging jets (Ref. 2) varied markedly with momentum ratio, with the mixing factor E_m exhibiting a sharp peak at a value of momentum ratio equal to the jets' diameter ratio. This last consideration would indicate less sensitivity of mixing, and therefore of performance efficiency, to variations in mixture ratio with impinging-sheet injectors, especially in small injectors consisting of relatively few elements, where the favorable effects of secondary mixing are felt to a lesser degree.

As noted in SPS 37-41, Vol. V, the N_2O_4/N_2H_4 propellant combination gave typical c^* efficiencies on the order of

[2]Rupe, J. H., private communication, November 8, 1967.

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98.5%. It would be expected that MDFA/N_2H_4 and MDFA/MMH, which are chemically similar, would give about the same combustion efficiency as N_2O_4/N_2H_4 when fired in the same injector and chamber. However, c^* efficiencies of only 95 to 96% were realized with the maximum-density acid combinations. One possible explanation for this apparent difference in combustion efficiencies may lie in the theoretical values of characteristic velocity used in calculating the c^* efficiencies. There is considerable doubt as to the validity of the heat of formation (−30.413 kcal/mole) used for the MDFA in the theoretical performance calculations. Thus, the theoretical values of c^* may be somewhat too high, and the values of η_{c^*} based on them, which are reported in Tables 1 and 2, may be one or two percentage points lower than the actually delivered values.

Another potential cause of the discrepancies in combustion efficiency noted with the different oxidizers may lie in chemical differences between them, resulting in slight differences in the mechanisms of mixing and atomization prevailing in the reactive environment. In any event, combustion efficiencies in excess of 95% are certainly attainable with the maximum-density nitric acid oxidizer in conjunction with MMH and N_2H_4.

Definition of terms

d orifice diameter, in.
r mixture ratio, oxidizer/fuel
m stream momentum flux, ft-lbm/s^2
ρ density, lbm/ft^3

Subscripts

$_o$ oxidizer
$_f$ fuel

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